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Study of Raman amplification in DPP-BOTDA sensing employing Simplex coding for sub-meter scale spatial resolution over long fiber distances

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Abstract

The impact of Raman amplification and Simplex coding is studied in combination with differential pulse-width pair Brillouin optical time-domain analysis (DPP-BOTDA) to achieve sub-meter spatial resolution over very long sensing distances. An optimization of the power levels for the Raman pumps, Brillouin pump and signal has been carried out through numerical simulations, maximizing the signal levels and avoiding at the same time nonlinear effects and pump depletion. A reduction of acoustic-wave-induced distortions in the Brillouin gain spectrum down to negligible levels has also been achieved by numerical optimization of the pulse width and duty cycle of return-to-zero Simplex coding, providing significant signal-to-noise ratio enhancement. Strain-temperature sensing over 93 km standard SMF is achieved with a strain/temperature accuracy of $34\mu\epsilon/1.7^\circ\text{C}$, and 50 cm spatial resolution throughout the fiber length.

Keywords: fiber optics, sensors, Brillouin scattering, coding

(Some figures may appear in colour only in the online journal)

1. Introduction

One of the most adopted approaches in distributed sensing is given by Brillouin optical time-domain analysis (BOTDA), thanks to its capability of measuring strain and temperature simultaneously. The possibility of this technique to achieve long sensing ranges with high spatial resolution using standard single-mode fiber (SMF) enables many practical applications in structural health monitoring and civil engineering. In some applications, such as crack detection in large civil structures, spatial resolution values ranging in the cm-scale are required over a few kilometers distance. Other industrial

fields, like pipeline monitoring in the oil and gas industry, would strongly benefit from temperature and strain distributed sensing capabilities over tens or hundreds of km SMF with tens of cm spatial resolution. However, the spatial resolution in standard BOTDA systems is limited to 1 m due to the acoustic-phonon lifetime (~ 10 ns), inducing a broadening of the Brillouin gain spectrum (BGS) when pulse widths shorter than 10 ns are used, thus leading to a reduction of the Brillouin peak gain [1] and to inaccuracies in Brillouin frequency shift (BFS) measurements. BOTDA can be employed to attain spatial resolution values below the meter-scale through the use of a differential pulse-width pair (DPP), and indeed DPP-BOTDA has recently enabled sub-meter spatial resolutions [1–3]. The main limitation in DPP-BOTDA is related to the DPP subtraction process, resulting in short sensing ranges

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due to reduced signal-to-noise ratio (SNR) levels. In standard BOTDA, in order to improve the SNR levels and extend the sensing distance exceeding the hundred-km range, bi-directional Raman amplification has been employed [4–6], although resulting in spatial resolutions of the order of the meter-scale. On the other hand, in DPP-BOTDA schemes, optical pulse coding has also been applied to increase the detected SNR levels and to achieve longer distances up to several tens of kilometers [1, 2].

Bi-directional low-RIN Raman amplification is studied in this paper in combination with optical pulse coding on DPP-BOTDA sensors, for first time to our knowledge, in order to provide distributed long-distance measurements together with sub-meter spatial resolution. Numerical optimization of experimental test-bed conditions allows for an effective implementation of such a sensor scheme. In particular, the optimization of all relevant system parameters has been performed in terms of Raman and Brillouin pump power levels, signal power, pump intensity noise (RIN) transfer to the probe signal, as well as in terms of modulation format. Long-distance sensing along ~ 93 km SMF length with strain (temperature) resolutions of $34 \mu\epsilon$ (1.7°C) is then experimentally attained through the combination of low-RIN bi-directional Raman amplification together with optical pulse coding (return-to-zero format Simplex codes) on a DPP-BOTDA scheme, enabling minimum 50 cm spatial resolution over 93 km distance.

2. Theory and simulations

BOTDA exploits stimulated Brillouin scattering (SBS), in which a pulsed pump beam and a counter-propagating continuous-wave (CW) probe beam, at different frequencies, interact through an acoustic wave. The SBS resonance frequency, named Brillouin frequency shift (BFS), is a temperature- and strain-dependent parameter that is exploited for distributed sensing. The BFS can be estimated along the optical fiber, providing information about the local temperature and strain at every fiber position. In standard BOTDA, the probe CW light experiences amplification at the expense of the pump power while it propagates along the fiber; thus, the probe intensity contrast (ΔI_{CW}) at the receiver can be then given as [2]

$$\Delta I_{\text{CW}}(t, \Delta\nu) \propto \int_{v_g t/2}^{v_g t/2 + \Delta z} g_B(\xi, \Delta\nu) I_P(\xi, \Delta\nu) d\xi, \quad (1)$$

where $\Delta\nu$ is the frequency separation between the probe and the pump, Δz is the interaction length (i.e. the spatial resolution) given by the pump pulse duration, v_g is the light group velocity, $g_B(\xi, \Delta\nu)$ is the BGS and $I_P(\xi, \Delta\nu)$ is the pump intensity. By tuning the frequency difference between pulsed and probe signals the BGS can be measured at every fiber position, giving the information about the local BFS. From equation (1), it can be seen that, when high spatial resolutions are required, the intensity contrast of the CW probe wave (ΔI_{CW}) is reduced, limiting then the SNR of the measurements [2]. In addition, the BGS is broadened when using a pump pulse width shorter than the acoustic-phonon lifetime (~ 10 ns),

thus reducing the peak Brillouin gain [3]. These two features lead to significant inaccuracy in BFS measurements with standard BOTDA for spatial resolution values below ~ 1 m [3]. Therefore, in order to achieve distributed sensing with sub-meter spatial resolution over long sensing distances, more refined schemes have to be employed. One common method to achieve sub-meter spatial resolution is DPP-BOTDA [1], where the Brillouin spectra originating from two different pulses with slightly different widths are subtracted, so that the spatial resolution is given by the pulse widths difference rather than the used pulse widths.

Thus, using pulse widths much longer than the acoustic-phonon lifetime, the BGS broadening is avoided, providing at the same time a high spatial resolution. The SNR values resulting from the subtraction of two BGS are typically low, leading to a reduced measurement accuracy in BFS (and consequently strain and temperature) estimation. Recently, the use of optical pulse coding was applied to DPP-BOTDA to enhance the sensing performance though the coding gain provided to SNR by Simplex coding [2].

Different unipolar codes are generally suitable for this kind of application, as, for instance, complementary-correlation Golay [1] or Simplex codes [7], which actually provide similar coding gain (and SNR enhancement) for a given code length. Simplex codewords, used in our experiments, are characterized by the feature that the number of ‘1’ bits (i.e. light pulses) in a codeword is constant for all codewords (and equal to $(L + 1)/2$ for a code length L), and hence, the effective length and maximum allowed peak power before the onset of nonlinearities is the same for all codewords. On the other hand, other pulse coding schemes, such as the ones based on Golay codes, are characterized by different number of pulses for different codewords; in such schemes the maximum usable power is limited by the codeword containing the largest amount of pulses. For this reason, Simplex codes appear especially effective for long sensing distances when the usage of maximum probe power is essential in order to ensure higher SNR levels. The SNR enhancement in BOTDA traces can be finally quantified by the coding gain defined as [8]

$$G_{\text{cod}} = \frac{L_c + 1}{2\sqrt{L_c}}.$$

In addition to coding, further sensing distance enhancement can be obtained if distributed optical amplification is also employed. In particular, the use of Raman amplification for standard BOTDA system was first proposed in [4]. However, to our best knowledge, the combination of Raman amplification with pulse coding in DPP-BOTDA systems has not been studied so far, and in particular the combined approaches do not appear straightforward due, e.g., to the linear response required by the decoding process when pulse coding is combined with DPP and Raman amplification. In this paper we combine the use of Simplex coding with low relative-intensity noise bidirectional Raman amplification in a DPP-BOTDA system to provide long-range sub-meter resolution.

In particular, the Raman amplification process has been optimized through numerical simulations in order to maximize the optical SNR (OSNR) of the probe signal reaching the

receiver, avoiding at the same time pump depletion and nonlinear effects.

Partial differential equations describing the coupled pumps and signal evolution [9] are numerically integrated. Considering that the Brillouin gain in BOTDA sensors is typically very low (in the order of a few per cent), the Brillouin interaction can be neglected with respect to the Raman gain (which provides an ON-OFF gain of several dB) while designing the distributed Raman amplifier (DRA). Our numerical simulations are based on a Raman-amplification spectral model describing the power evolution of co- and counter-propagating Raman pumps, an arbitrary number of signals (in our case Brillouin pump and probe), forward and backward amplified spontaneous emission (ASE) components and double Rayleigh scattering (DRS) effects. In compact notation, the model can be written as [9]

$$\begin{aligned} \frac{d}{dz} P_i^\pm(z) = & \mp \alpha_i P_i^\pm(z) \pm \gamma_i P_i^\pm(z) \\ & \pm \sum_j C_{ij} P_j^\pm(z) [P_j^+(z) + P_j^-(z)] \\ & \pm 2h\nu_i^\pm \Delta\nu \sum_j C_{ij} [P_j^+(z) + P_j^-(z)], \end{aligned} \quad (2)$$

where the subscripts i and j denote the optical signals propagating at wavelengths λ_i and λ_j , respectively; $P_i^+(z)$ and $P_i^-(z)$ are the respective forward and backward propagating powers; α_i is the fiber attenuation; γ_i is the Rayleigh scattering coefficient; ν_i is the optical frequency corresponding to the wavelength λ_i ; h is the Planck constant; $\Delta\nu$ is the resolution bandwidth of the ASE light; and C_{ij} is the Raman gain/depletion term between wavelengths λ_i and λ_j given by [9, 10]

$$C_{ij} = \frac{g_{ij}}{A_{\text{eff}} K_{\text{eff}}} \quad \text{for } \lambda_i > \lambda_j \text{ (gain term),}$$

$$C_{ij} = \frac{-g_{ij}}{A_{\text{eff}} K_{\text{eff}}} \frac{\lambda_j}{\lambda_i} \quad \text{for } \lambda_i < \lambda_j \text{ (depletion term),}$$

where g_{ij} is the Raman gain coefficient between wavelengths λ_i and λ_j , A_{eff} is the effective area of the fiber, and K_{eff} is the polarization factor. Note that this model allows for an accurate calculation of both signal-to-ASE-noise and signal-to-DRS-noise ratios for Raman amplification performance analysis [10]. Considering that in a well-designed DRA the ASE noise is expected to be the dominant noise contribution, we first carry out the design of a bi-directional DRA considering ASE and DRS noise based on the system of equations (2). Then, the detrimental impact of the pump RIN transfer to the BOTDA signals (i.e. Brillouin pump and probe wave) is analyzed separately, devoting a special attention to the pump co-propagating with the probe signal, due to the efficient RIN transfer taking place in such a case [9, 10]. In order to optimize the input power levels for the Raman pumps, Brillouin pump and probe signal, the system of equations (2) has been solved numerically for a wide range of boundary conditions (i.e. input power levels) using a fourth-order Runge–Kutta method followed by a multi-step iterative process along forward and backward directions. Since the effective length of the Raman amplification process (~ 20 km in SMF) is much shorter than

the total length (~ 93 km), the input power optimization for the forward-propagating signals (i.e. Brillouin pump and forward-propagating Raman pump) can be carried out independently from the one for the backward-propagating signals (i.e. Brillouin probe and backward-propagating Raman pump) [6]. The optimization process for the forward-propagating signals aims at the maximization of the Brillouin pump power at the far fiber end, avoiding however that the maximum power inside the fiber exceeds the onset of nonlinear effects (i.e. 100–200 mW, limited by the threshold level of modulation instability).

Dealing with SBS effects, in order to fully exploit the benefits of our technique, optimized return-to-zero pulses have to be used on the Brillouin pulsed pump. In this case we have followed the optimization process reported in [2], which indicates that pulse widths longer than ~ 60 ns are required to maximize the DPP Brillouin gain. In addition, to avoid SBS gain interaction among the different pulses within the code sequences (resulting from pre-excited acoustic waves), a bit slot longer than 110 ns has to be used. In particular, in order to achieve a theoretical spatial resolution of 40 cm and to maintain a linear SBS gain for all coded pulses, a bit slot of 120 ns and a DPP of 60/56 ns (representing a duty cycle of 50%) are used in this case.

As previously discussed, since the quasi-CW model for Raman amplification can be assumed to be valid for the case of a Brillouin pump employing return-to-zero pulse coding, the optimum input power levels for the forward propagating signals in this case are found to be similar to the single-pulse case. Thus, following an optimization procedure such as the one reported in [6], in which the output Brillouin pump power is maximized, it has been found that the optimum levels for the forward-propagating Raman pump and the coded Brillouin pump are 400 and 10 mW, respectively. These input power levels maximize the Brillouin power at the far fiber end, and avoid at the same time nonlinear effects in the sensing fiber.

Then, using the optimum Brillouin pump and probe power, the input power levels for the backward propagating signals have been optimized following a similar procedure. In this case the objective is to maximize the optical SNR (OSNR) of the probe signal reaching the receiver; however, considering that long pulse sequences would induce a large Brillouin gain in the probe signal, the probe power should be kept low enough to avoid pump depletion. The optimum levels for the backward propagating signals can be found by inspection of the simulation contour plot shown in figure 1, which reports the probe OSNR reaching the receiver side (solid lines) and the minimum pump-probe difference (dotted lines) versus backward-propagating Raman pump power for several input probe powers. Thus, a high probe OSNR and a pump-probe power difference better than 15 dB (similar to the conditions in [6] to allow some power margin) can be obtained with a probe power of -13 dBm and a backward Raman pump of 300 mW (indicated with a star in figure 1).

In addition, while the use of a low-RIN backward Raman pump is critical in order to minimize the noise transfer to the probe signal, the RIN characteristics of the forward Raman pump do not play a key role and can be neglected in the simulations due to the low transferred noise in the backward Raman amplification process.

Figure 1. Contour plot showing input power optimization for probe signal and backward-propagating Raman pump.

3. Experiment

The used setup is shown in figure 2. The output of a distributed feedback (DFB) laser is split into two (probe and pump) branches by a 3 dB coupler. In the probe (CW signal) branch a Mach-Zehnder modulator (MZM) is used to generate two sideband components suppressing at the same time the carrier frequency. A polarization scrambler is also used to depolarize the CW signal in order to reduce the polarization dependent gain (PDG), thus enhancing the performance of the sensor. A variable optical attenuator and an optical isolator are employed in order to adjust the amount of optical probe power into the sensing fiber and to isolate the transmitter from the optical counter-propagating components respectively. In the pump (pulsed beam) branch, an EDFA and another MZM driven by a waveform generator are used to amplify the DFB laser output and then to generate sequences of 127 bit Simplex optical codes. The position of the EDFA before the MZM avoids distortion in the codeword. Automated feedback controls for both MZMs ensure time stability and improved measurement repeatability. Another scrambler is used in the pump branch to depolarize the pump

pulse signal. Bidirectional distributed Raman amplification has been implemented by coupling two Raman pumps at 1450 nm (in forward and backward directions) into a ~ 93 km SMF. A depolarized fiber Raman laser (FRL) is used as forward-propagating Raman pump, while the backward-propagating Raman pump has been implemented using two low-RIN polarization-multiplexed Fabry-Perot (FP) lasers ($\text{RIN} < 130 \text{ dB Hz}^{-1}$), thus avoiding probe signal fluctuations due to polarization-dependent Raman gain and pump-to-probe RIN transfer. At the receiver, a linear-gain EDFA is used as a preamplifier for the received traces. A circulator and a fiber Bragg grating (FBG, 6 GHz bandwidth, within an athermal packaging providing temperature-compensation and a FBG response which is insensitive over a large range of environmental conditions) have been used to filter out the preamplifier ASE noise, the residual suppressed carrier, the Brillouin anti-Stokes line and the Rayleigh signal. Finally, a 400 MHz PIN photo-receiver and an analogue-to-digital converter (ADC) have been connected to a computer for trace acquisition. Input power conditions for Raman pumps, Brillouin pump and probe signals have been set according to the simulation results reported in the previous section, thus avoiding nonlinear effect and minimizing pump depletion and the RIN impact. Note that Simplex coding gain can be exploited either to improve the resolution for the same number of acquired traces, or to reduce the acquired traces without penalizing the resolution (performing fewer averages) for faster measurement. In our case the overall acquisition time is of the order of a few minutes.

4. Results

Referring to the set-up of figure 2, the CW probe frequency has been swept by the RF signal generator within a 50 MHz range around a pump-probe frequency difference of ~ 10.88 GHz. The Brillouin pump has been intensity-modulated according to Simplex coding with 127 bit code length, using DPPs of 60/56 ns; the codeword shows a return-to-zero format (120 ns bit slot, 50% duty cycle) as explained above; this feature avoids patterning effects potentially arising from acoustic-wave pre-excitation in the decoding process. The best-attainable spatial

Figure 2. Experimental setup.

Figure 3. Decoded BGS obtained by the DPP-BOTDA along the sensing fiber (at room temperature).

Figure 4. BFS versus distance (whole fiber at 27.5 °C).

resolution with the pulse-width difference of 4 ns is then 40 cm. Since the probe OSNR at the receiver is enhanced by the distributed fiber Raman amplification, we also observe higher SNR in the DPP-BOTDA-trace difference, with the possibility then to reach sub-meter spatial resolution over many tens of kilometers. For each scanned frequency value, the coded traces for 56 ns and 60 ns pulse widths are acquired and decoded, and finally the trace pairs are then subtracted as required in the DPP scheme. The 93 km long sensing fiber is composed of three fusion-spliced fiber spools (25, 58 and 10 km length), and is initially placed at room temperature (~ 27.5 °C). The BGS obtained along the fiber length by the subtraction of differential pulse-width is shown in figure 3, where it can be noticed that the lowest SNR occurs at a distance of about 70 km.

The BFS has then been obtained by the BGS through a Lorentzian-shape fitting along the whole fiber, and is reported in figure 4, pointing out the existence of three slightly different BFS values along the fiber, corresponding to fiber spools with different physical characteristics, and giving rise to BFS steps (~ 3 MHz) at 25 and 83 km.

Such small differences in the BFS typically originate from slight non-uniformities in the manufacturing parameters, which are common even in different lots from a single fiber manufacturer. Considering that such frequency differences

Figure 5. Decoded BGS along the fiber end (heated fiber spool at 43 °C).

Figure 6. Fiber temperature around 93 km distance.

(~ 3 MHz) are small in comparison to the BGS linewidth (~ 30 MHz), a continuous SBS interaction is then expected to take place along the whole fiber length, corresponding to the worst-case condition in terms of pump depletion and non-local effects. Considering the used power values, and analyzing the spectral shape of the Brillouin gain throughout the fiber length, pump depletion effects can be considered as negligible.

In order to verify the performance of the implemented sensor, 10 m of fiber at ~ 92.7 km distance have been placed inside a temperature-controlled chamber (TCC), whose temperature has been set to 43 °C, while the rest of the fiber is placed at room temperature (27.5 °C). In order to observe the induced variations in BFS, the BGS measurement versus distance around the far fiber-end is shown in figure 5; in the figure, the BGS shift induced by heating can be clearly observed in the last few fiber meters.

Similarly to the previous case, the BFS profile can be obtained through a Lorentzian fit, and then the temperature variations can be easily estimated from the BFS temperature coefficient in SMF (~ 1 MHz/°C). Figure 6 then shows the estimated temperature near the far fiber-end (at 92.7 km), confirming the ~ 15 °C increase in the heated spool with respect to room temperature (27.5 °C). In order to estimate the experimental spatial resolution, the step of the measured temperature variation has then been analyzed. The attained

Figure 7. Attained temperature resolution versus distance.

Figure 8. FWHM of measured BGS along fiber length.

spatial resolution (measured as the 10%–90% response of the temperature variation) near the fiber end is indicated in figure 6, and results to be ~ 50 cm, which is close to the theoretical limit of 40 cm with our DPP scheme.

The attained temperature–strain resolution along the fiber length has been calculated as one standard deviation resulting from the BFS measurements, and is shown in figure 7; the worst-case temperature (strain) resolution is observed at ~ 70 km distance, where the lowest OSNR occurs due to minimum Raman amplification, as also evident from figure 3. The worst-case resolution results to be ~ 1.7 MHz, corresponding to ~ 1.7 °C temperature resolution (or ~ 34 $\mu\epsilon$ if strain is sought after).

In addition to the Lorentzian shape of the BGS, the full-width-at-half-maximum (FWHM) of the BGS is a good indicator that the spectral shape is not distorted along the fiber due to, e.g., nonlinear effects or pump depletion. The measured Brillouin FWHM in our experimental scheme is shown in figure 8. The FWHM reported in figure 8 appears constant throughout the fiber (apart from noisy behavior due to the low SNR levels, in particular around the minimum gain region at ~ 70 km distance), its mean value being of the order of 30–35 MHz, as expected in a non-distorted BGS in SMF. Note that the optimization of the Raman and Brillouin pump power levels, together with the low Raman pump RIN,

allow for reduced nonlinear penalties and a small cross-talk due to RIN transfer during Raman amplification of the CW probe. Furthermore, in this case the use of optimized Simplex-coded pulses with a return-to-zero modulation format (50% duty cycle) avoids acoustic-wave pre-excitation and related penalties.

5. Conclusion

In conclusion, we studied and implemented a DPP-BOTDA sensor combining Simplex coding in Brillouin pump and low-RIN bi-directional Raman amplification, aiming at hundred-km range and sub-meter resolution values. A numerical optimization study of the experimental conditions in terms of Brillouin and Raman gain distributions, as well as the use of low-RIN Raman pumping, has allowed us to maximize the received SNR, avoiding at the same time potential penalties due to nonlinear effects, pump depletion and RIN transfer. Experimental results with the built DPP-BOTDA scheme have demonstrated distributed sensing capabilities over 93 km of standard SMF, attaining 50 cm spatial resolution along the fiber and a worst-case accuracy in BFS better than ~ 1.7 MHz throughout the fiber length.

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